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Commentary on Fast Atmospheric Pulsations

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In a recent paper, LaBelle [1987] proposed that Fast Atmospheric Light Pulsations (FAPs), which have been observed at L=1.5-2.2 in the northern hemisphere, are optical signatures of >2 MeV electrons associated with Lightning-Induced Electron Precipitation (LEP) events produced by lightning strokes in the southern hemisphere. FAPs cannot be produced by >2 MeV electrons in the inner radiation belt because the upper limit for fluxes of such particles is only about 0.2% of the value that was used in the analysis and would lead to an unrealistically short electron lifetime. The discrepancy comes from using an electron model, AE-2, which included the Starfish fission electrons. Later inner zone electron environment models, which agree with measurements made in 1968 and in 1976, show the inner-zone to have negligible fluxes of electrons in excess of 2 Mev. ~~Additionally,~~ the use of a model in which southern hemisphere lightning strokes result in northern hemisphere FAPs via a cyclotron mode interaction between magnetospheric electrons and lightning-generated waves is also untenable.

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because it would result in FAP intensities two orders of magnitude greater in the southern hemisphere than in the northern hemisphere, leading to a further two orders of magnitude reduction in estimated inner zone electron lifetimes. Although the LaBelle [1987] model cannot be correct, the estimated light intensity of FAPs is within acceptable bounds compared to the lifetime of inner zone electrons if all electrons above 100 keV contribute to the light production, if southern hemisphere FAP intensity is no greater than the FAP intensity observed in the northern hemisphere, and if the light-production efficiency is of the order of 10^{-3}. .001. Key words → to field 18

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PREFACE

The author expresses his appreciation for a helpful discussion with M. Schulz in the preparation of this report.

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I. INTRODUCTION

In "Are Fast Atmospheric Pulsations Optical Signatures of Lightning-Induced Electron Precipitation?", LaBelle (Ref. 1) makes a case for fast atmospheric pulsations (FAPs) being produced by lightning-induced electron precipitation (LEP) events. The FAPs being discussed were observed in the vicinity of L=1.56 during the 1970-1972 period [Ögleman (Ref. 2)] and from 1972 to 1976 [Tümer (Ref. 3)]. The proposed mechanism is as follows: A lightning stroke in the southern hemisphere produces electromagnetic waves which couple with the magnetosphere and propagate in the whistler mode to interact with energetic electrons via a cyclotron resonance. The electrons are scattered by the interaction and their mirror points are lowered (on average, since the initial pitch-angle distribution is anisotropic) so that they interact with the neutral atmosphere, producing a sub-millisecond flash of visible light with the characteristics of a damped 10 kHz oscillation. To account for the short duration of the FAP, the interaction is said to occur over a short ($\leq$ 300 km) region of field line; invokes electron penetration into the atmosphere to a 70-80 km altitude where the collision frequency is 10^5 sec^{-1} or higher (which requires a minimum of 0.1 MeV electron energy to penetrate to that depth); and also invokes > 2 MeV electrons as the agent in order to satisfy the requirement for low temporal dispersion. The author provides a number of statistics: an average rate of FAPs of 10^{-4} sec^{-1}; an average electron energy flux of 10^{-3} ergs cm^{-2} per event (assuming a light production efficiency of 10^{-4}); and, an average electron energy of 1 MeV to get an average precipitated electron flux of 6 x 10^2 electrons cm^{-2} per event, resulting in a loss rate of 6 x 10^{-2} cm^{-2} sec^{-1} at the atmosphere. This is equivalent to 3 x 10^{-2} cm^{-2} sec^{-1} at the equator (including a factor of 2 to account for the divergence of the field lines at L=1.5). He then states that the total omnidirectional electron flux for energies above 0.5 MeV in the inner belt is of the order of 10^8 electrons cm^{-2} sec^{-1}, citing Vette et al. (Ref. 4). It is at this point that a problem with the model arises. The resulting numbers indicate a

trapped lifetime due to LEP events alone of 4×10^3 days, "comparable to the lifetime estimated from Coulomb scattering for these energies (Ref. 5)."

II. DISCUSSION

The Vette et al. reference is the AE-2 model (Aerospace Electrons, version 2) which is a circa 1964 model that includes the Starfish fission electrons. By 1968 most of the Starfish electrons had been lost, their characteristic lifetime having been about 400 days (Ref. 6). Measurements of electrons with energies much above 1 MeV in the inner zone were quite difficult to make because the fluxes were very low compared with the fluxes of very energetic protons which constitute an undesired background in all particle measuring instruments. [Typical fluxes of protons, $E_{p+} > 100$ MeV, are of the order of 6×10^3 cm^{-2} sec^{-1} at L=1.5 (Ref. 7)]. During large magnetic storms, when large quantities of electrons are accelerated in the outer zone and diffuse radially inward, some energetic electrons do survive traversal of the slot to become trapped in the inner zone (Ref. 8), but these events are rare and the number of electrons with energies above 1 MeV which are injected is very small. For almost all practical purposes, electrons with energies above 1 MeV can be ignored in the inner zone. In the present case, however, such particles are required for the proposed mechanism.

A more recent inner-zone electron model, AE-6 (Ref. 9), indicates an integral omnidirectional flux >0.5 MeV of the order of 5×10^6 rather than the 10^8 used above. At 2.0 MeV, the respective numbers are 1.2×10^5 vs. 8.3×10^6 for the AE-2 model. A comparison of the AE-6 model with orbital data (Ref. 10) shows that by 1968, the energetic Starfish electrons had decayed to the level of the AE-6 model. With the 400-day characteristic life mentioned above, another order of magnitude decay might have been expected to have occurred by late 1970 when the first FAP observations were made (Ref. 2) and yet another two orders of magnitude by the time the latest Tümer (Ref. 3) observations were made.

The energetic electron flux, however, did not diminish to that extent. Figure 1 is extracted from Vette et al. (Ref. 4) and presents the AE-2

electron energy spectrum at L=1.5 in comparison with newer models and with in situ measurements. The two data curves are both reduced to appropriate units to be compared directly in energy and intensity with the AE-2 model. One curve, with triangles denoting data points, was obtained from a paper by West and Buck (Ref. 11) and is the measured equatorial spectrum at L=1.5 in 1968. The second curve, with data points denoted by filled circles, is unpublished data obtained in July 1976 by the energetic electron spectrometer on the S3-3 satellite. Also plotted are representative points from the later National Space Science Data Center (NSSDC) models AE-5 (Ref. 12) and AE-6 (Ref. 9). The S3-3 equatorial differential energy spectrum at L=1.5 is fitted very well by two power-law curves: $N_E = 1 \times 10^6 E^{-2.87}$ over the energy range 0.1 MeV to 0.66 MeV and $N_E = 5.5 \times 10^5 E^{-4.38}$ above 0.66 MeV where E is in units of MeV.

Figure 1 shows that AE-6 is an appropriate electron flux model to use, at least at L=1.5, and that the high energy portion of the inner zone electron spectrum did not continue to decay exponentially past about 1968. Note, however, that the correct value for energy flux at the equator at L=1.5 will decrease by a much larger amount than the number flux since it is the higher energy electrons that are greatly reduced with respect to the spectrum used in the analysis by LaBelle. Note, also, that these data are all at L=1.5, while the FAP observations were made at Ankara, Turkey, in the vicinity of L=1.56. At L=1.56, the observed fluxes are lower than the L=1.5 numbers by about 25%. The difference is not a significant one for calculations relating to the FAP mechanism. Also, the FAPs were observed to be centered to the south of a northern-hemisphere observing station, indicating that they were occurring at a somewhat lower L-value than 1.56 (Ref. 2).

Further minor discrepancies (factors of 1.5 to 2) in the LaBelle analysis are the use of a bounce time representative of electrons with zero pitch angle at the equator rather than the smallest angle which can traverse the South Atlantic anomaly region (about 37° for L=1.5); the reduction of flux at the equator relative to the atmospheric loss point due

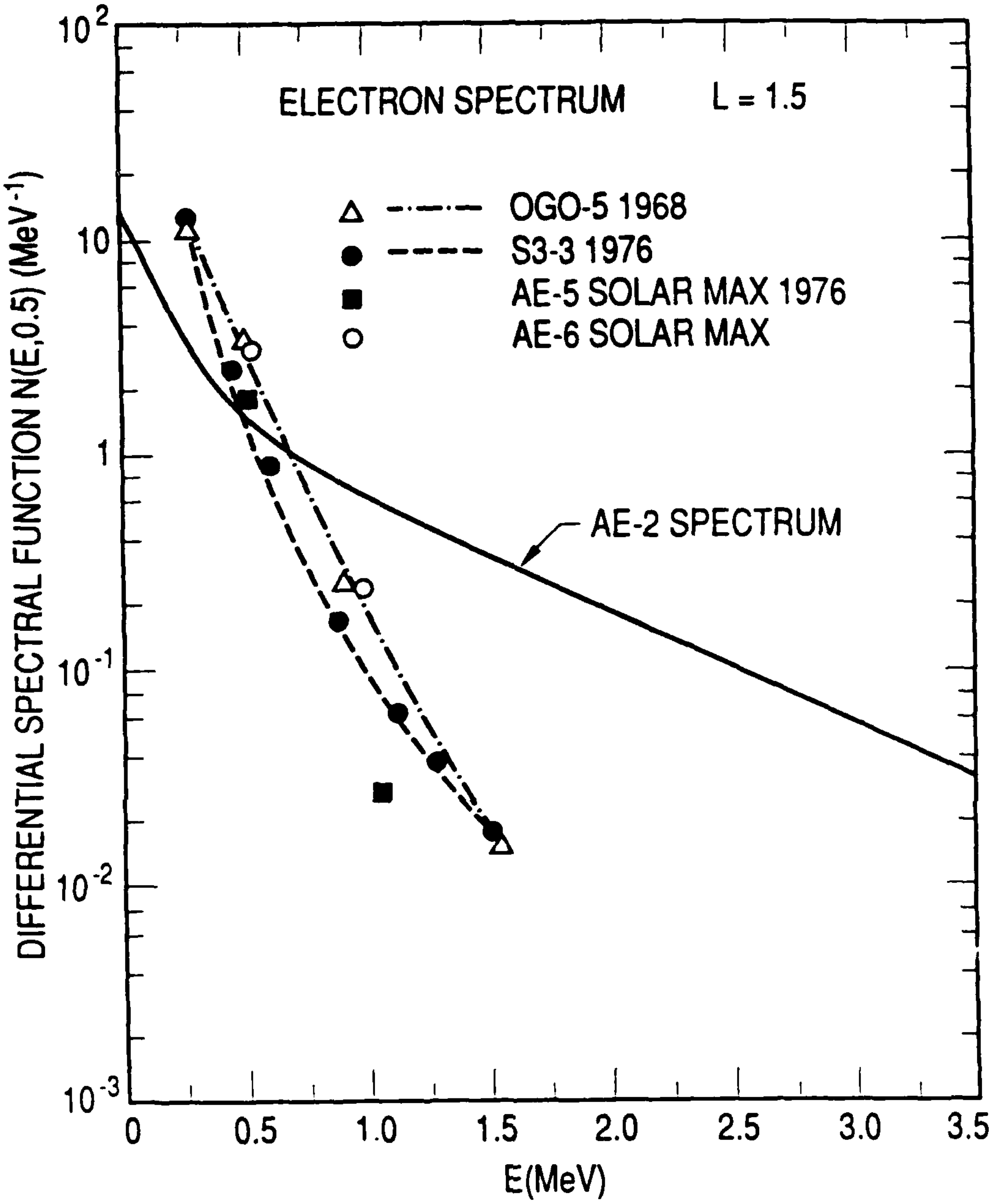

Fig. 1. Spectral Plot (Solid Curve) at L=1.5 Using the AE-2 Model Environment [Vette et al., Ref. 4] Reproduced from That Document. The other curves are in situ measurements of the electron environment made at L=1.5 in 1968 and 1976. Other electron models are also plotted with individual points. All values have been converted to the convention used in the AE-2 plot. Note that all models and data agree very well in the 0.5 MeV region but the AE-2 model contains far more flux at higher energies because it represents a combination of the natural and Starfish electrons.

to the divergence of the field; and, the use of 1.0×10^8 electrons with an average energy of 1 MeV instead of the AE-2 model's 1.19×10^8 omnidirectional flux factor above 0.5 MeV with an average energy of 1.6 MeV. These minor inaccuracies almost precisely cancel: the more precise calculations result in a number within 4% of the result obtained by LaBelle and so will not be considered further.

Using realistic number fluxes and energy spectra for the 1970-1976 time period at the equator and integrating the experimentally determined pitch-angle distribution from the S3-3 data along the L=1.5 field line to the minimum trapped B_{mirror} (0.248 gauss, imposed by the 100 km altitude B at the longitude of the South Atlantic anomaly), one obtains the number fluxes and energy fluxes shown in Table 1. The ratios of the AE-2 numbers to the S3-3/AE-6 numbers (third line in the table marked "AE-2/S3-3") are the factors by which the calculated lifetimes against LEP precipitation presented by LaBelle should be reduced. These numbers would give LEP-caused lifetimes of about 200 days if the >0.5 MeV flux were used and a lifetime of about 10 days if the >2 MeV fluxes were used.

Table 1. Electron Fluxes and Energy Fluxes at L=1.5

	N>0.5 MeV*	N>2.0 MeV	E>0.5 MeV#	E>2.0 MeV
AE-2	1.19 x 108	3.8 x 107	1.9 x 108	1.0 x 108
S3-3	8.3 x 106	8.9 x 104	9.8 x 106	2.4 x 105
AE-2/S3-3	14.3	427	19.4	417

*In units of e-/cm^2-sec #In units of Mev/cm^2-sec

An even more serious problem than the use of the AE-2 electron model is the conjectured location of the lightning stroke. The peak of occurrence of FAPs is in the winter while the thunderstorm frequency in Turkey peaks in the summer. This is explained by resorting to a peak in the thunderstorm occurrence at the conjugate point in southern Africa which is

then in summer. For the cyclotron resonance utilized in the explanation of the phenomenon, the lightning-generated waves must be travelling in a direction opposite to that of the interacting particles. Whistler-mode waves generated in the southern hemisphere would be northward-going and would interact with southward-going particles, resulting in electrons with lowered pitch-angles which are moving in a southward direction. The first interaction would be with the atmosphere in the southern region if their mirror B was high enough to mirror within the atmosphere. At 100 km altitude (the top of the atmosphere) at the longitude of Ankara, 33° E, the L=1.5 field line has an intensity of .303 gauss in the southern hemisphere and .448 gauss in the northern hemisphere. The reflection coefficient for radiation belt electrons at the top of the atmosphere is less than 1% (Ref. 13). Thus, more than 99% of the electrons pitch-angle scattered by waves originating in the southern hemisphere would be lost into the atmosphere in the southern hemisphere. In order for the electrons to precipitate above Turkey prior to mirroring in the southern hemisphere, the whistler-mode waves generated in the southern hemisphere would have to propagate through the magnetosphere to a northern hemisphere reflection point without significantly interacting with the energetic electrons, be reflected with about a 5% reflection coefficient (Ref. 14); then propagate back up the field line to the equator and there pitch-angle scatter the energetic electrons. This is a highly improbable scenario.

It follows that, if lightning in the southern hemisphere were the cause of the FAPs observed in the northern hemisphere, the original intensity of the FAP in the southern hemisphere would have to be 2 or more orders of magnitude greater than that which is observed in the northern hemisphere. This rules out any possibility that FAPs observed in the northern hemisphere are due to LEPs produced by lightning-generated waves in the southern hemisphere in interaction with electrons on the field line prior to the wave being reflected at the northern hemisphere ionosphere, since this would produce electron lifetimes which are 2 or more orders of magnitude shorter than those calculated above. This would result in elec-

tron lifetimes at L=1.5 of less than 2 hours for >2 MeV electrons, if they were the energy source, and less than 2 days if the energy source were the >0.5 MeV electron population.

Clearly, the FAPs are not caused by LEP events in the southern hemisphere with >0.5 MeV electrons, and especially not by the >2 MeV electrons, in the mechanism proposed in LaBelle. Even if one assumes a 10^{-3} efficiency in transforming electron energy to light (Ref. 16) instead of the 10^{-4} efficiency used in the LaBelle analysis, these numbers are changed to 20 hours and 20 days, still far shorter than the measured lifetimes in the order of 400 days (Ref. 6). It thus appears that the mechanism proposed by LaBelle is either incorrect or significant unknown factors have not been taken into account in the analysis.

The requirement for atmospheric penetration of the electrons to 80 km (to obtain a collision frequency high enough to explain the short duration of the FAPs) limits the minimum energy of the particles producing the light to about 0.1 MeV. Electrons up to 1.2 MeV have been observed to diffuse into the inner zone down to about L=1.5 after magnetic storms. Vampola (Ref. 17) and Ögleman (Ref. 2) observed a correlation between the FAPs and the solar flare index. Could electrons with energies above 0.1 MeV be the source of the energy? Integrating the energy contained in the electron distribution between 0.1 MeV and 0.5 Mev results in a figure of 3.7×10^7 (in units of MeV/cm^2-sec) for the omnidirectional energy flux at the equator. This is a factor of 4 higher than the energy flux above 0.5 MeV. The bounce time is significantly longer (by about 50% at 0.1 MeV compared to 0.5 MeV). If the energy contained in this part of the electron population could also be used in the production of the FAPs, in addition to the >0.5 MeV particles, the lifetime estimate would be increased by a factor of 6. The resulting electron lifetime is still only 120 days, under the assumption that the interaction is with waves going upward in the southern hemisphere even if an efficiency of 10^{-3} is used for converting electron energy into light of the appropriate wavelength. Thus even extending the minimum electron energy down to 0.1 MeV will not suffice to permit the LaBelle model to work.

Another question which might be asked is: Can inner zone electrons be ruled out as the energy source for FAPs? The answer is "No". Using a conversion efficiency of electron energy into light of 10^{-3}, an energy source consisting of all of the electron population above 0.1 MeV, and an assumption that the observed intensity of the FAP light emission is the result of the first interaction of the electrons with the atmosphere (the electrons have not been backscattered from the atmosphere in the southern hemisphere), one would get an estimated inner zone electron lifetime in the order of 1200 days. In this revised scenario, ample energy is available for the electron population to be the source of the energy observed in the FAPs. However, even ignoring lightning as a causative agent, there would still be two major difficulties: the short duration of a FAP, and the 10 kHz microstructure observed in the FAPs. The short duration of the FAP now becomes a serious difficulty because the difference in the bounce period between the 0.1 MeV electrons (0.195 sec) and 0.5 or 1 MeV electrons (0.125 and 0.115 sec, respectively) is 2 orders of magnitude larger than the FAP duration. Electrons with this spread of energies which were pitch-angle scattered just a few hundred kilometers above the atmosphere would have a dispersion in arrival times in excess of the length of the FAPs. The 10 kHz microstructure observed in FAPS is also a serious difficulty since a 100 μs period is orders of magnitude shorter or longer than characteristic times associated with magnetospheric phenomena, such as wave propagation along the field line (the order of 1 second), particle bounce periods (a tenth of a second), electron gyration periods (a few msec), etc.

If the measured FAP intensity is being observed in the same hemisphere in which waves propagating up the field line produce electron scattering, the analysis above would lead to a lifetime of about 1200 days for the inner zone electrons. The measured lifetime of energetic electrons in the inner zone is of the order of 400 days for a wide range of energy over the range of L=1.4 to 1.75 (Ref. 6). Neither scattering by the residual atmosphere nor radial diffusion to lower altitudes, where atmospheric scattering is more intense, can adequately explain this short lifetime. It may be

possible to use the FAP-calculated energy loss rate to explain the inner zone energetic electron lifetime. Perhaps the FAP is evidence of the electron removal process. The arguments contained in this comment do not rule out lightning as the cause of FAPs, only the LaBelle scenario. We agree with LaBelle's statement that FAPs warrant further investigation. Another parameter which might be of use in addressing whether FAPs are due to LEPs would be the diurnal variation of FAPs. The ionosphere is much more absorbing to VLF waves during the day than at night, by about 35 db, and FAPs should be much stronger and much more common at night.

A final comment: LaBelle states "...the inner radiation belt...contains higher fluxes of energetic electrons (> 500 keV) than does the outer belt." This should be qualified, since after major magnetic storms, the differential electron flux at 0.5 MeV on a given field line in the outer zone can be an order of magnitude greater than that which occurs in the inner zone (Ref. 17). The spectrum in the outer zone is typically much harder and the loss cone smaller, resulting in integral omnidirectional fluxes above 0.5 MeV and 2 MeV that are, respectively, more than 1 and more than 2 orders of magnitude greater that those which are present in the inner zone. The longer bounce period for electrons in the outer zone results in a total energy flux on the field line that is even greater.

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